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Research paper

Influence of gamma irradiation on the characteristic and dielectric properties of XLPE / Nano-silica composite

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Abstract

This paper investigates silica nanomaterial-based on cross-linked polyethylene (XLPE) for enhancing the electrical and mechanical properties in the insulation of power cables. The electrical cable insulation properties have been improved by adding a certain amount of spherical nanoparticles of fumed silica in a matrix of the polymer. Also, this paper has studied the impact of aging on XLPE and XLPE/SiO2 cable electrical parameters. The morphology of composite XLPE/SiO2 nanocomposites was characterized by scanning electron microscopy and the accelerated aging experiment was performed by 60Co gamma-ray source. It found that XLPE/SiO2 nanocomposites had better dielectric and mechanical properties; XLPE with 1 % Nano silica was found the optimal loading fraction where the breakdown voltage of the Nano silica samples is greater than that of the XLPE sample during low-dose gamma irradiation, while the breakdown voltage of both is reduced at high doses of radiation. Furthermore, electrical capacitance and dielectric constant were decreased by about 54% and 52%, respectively, over the unfilled XLPE at 50 KGy compared to XLPE/SiO2 at optimal loading fraction. Although the tensile strength for 1% XLPE/SiO2 decrease with increasing the radiation dose the elongation increase and give more elasticity and stability in the mechanical properties.

Keywords: *Cable Insulation; Electrical and Mechanical Properties; Gamma Irradiation; Sio2 Nanofillers.*

1. Introduction

The use of electrical insulation cables with specific characteristics and properties is an important requirement in radiological facilities and nuclear power plants. The most important of these properties are the mechanical properties, durability, dielectric properties, thermal characteristics and radiation properties of these electrical insulation cables at long time [1]. In order to obtain the required properties as well as to improve some other properties, there should be a possibility to change the materials of installation that fall into the manufacture of cables insulation, especially nanotechnology material, which is added to the main polymer, such as nano-silica or nano-clay. Also, when starting the construction of nuclear power plants must be safe and economical by connecting to an electrical network that has sufficient capacity to send and store the energy produced by the nuclear plant [2]. One of the most important safety requirements in the nuclear plant is the operation, shutdown or emergency and the existence of a cooling system that works for a long period of time after the shutdown of the station. In emergency situations when the cooling system is insufficient, there is a very serious to the reactor core and nuclear fuel, which can lead to release of the radiation plume and environmental pollution [3]. In fact, the security and safety systems in the nuclear power plants depend on the measurement and control devices low voltage Cables [4] inside the containment area, cables operate in severe environments, characterized by relatively high temperature and gamma-irradiation [5]. Several stresses can lead to insulation aging: the degradation causes the polymers to become more and more brittle, thus no more useful as cable electrical insulation which requires good mechanical and electrical properties.

XLPE has been observed to be very resistant to chemical and thermal degradation and for its high breakdown strength, high mechanical strength, excellent thermal stability, ease of manufacture, low cost, and low electrical losses [6, 7]. However, the electrical aging of the insulation in high voltage power cables is certain. Many strategies have been adopted in the development of high-performance cable insulation materials [8-10]. The application of many polymer nanocomposites to insulation material had been employed to guarantee the high reliability of the insulated systems [11], [12]. Significant questions remain, however, regarding the effects of gamma irradiation on XLPE and the combined effect of gamma radiation exposure [13], [14]. Irradiation of XLPE without filler and XLPE/nano-filler samples will be carried out with different doses use ^{60}Co source of gamma facility and measure the electrical and mechanical characteristics.

Many scientific research groups were interested in enhancing the electrical and mechanical properties of insulating cables used in NPP by functionalizing the surface of nanoparticles. From them, Greve, Eric [15] are reviewed aging mechanisms of two polymeric insulation materials that are used widely in nuclear power plant low-voltage cables, (XLPE) and (EPR/EPDM). Within the dispersion, agglomeration was found only for XLPVA nano dielectrics with TiO_2, with particles on the order of 100 μm in diameter at 3 wt %. Improvements in dielectric breakdown strength and conductivity were observed for certain configurations of PVA/XLPVA nano dielectrics between 1 and 5 wt %, depending on the specific

nanoparticle composition. Mareau Christophe [16] deals with properties of irradiated NPP cables which show significant changes after limited years of uncontrolled environmental conditions due to post-irradiation effects. Which conclude that once a polymer is irradiated with high dose rates, like e.g. due to a nuclear accident, insulation condition changes even after limited years from the event.
Indeed, it has been shown that degradation evolves over time even when the radiation or other stress sources are turned off.

2. Experimental work

2.1. Materials

XLPE was provided from El-Sewedy Electric –Egyplast cable in Egypt. XLPE permit to carry large current under normal (90 °C), emergency (130 °C) or short circuit (250 °C) conditions [17]. Table (1) shows the properties of the XLPE.

Table 1: Properties of the XLPE

Properties	Typical value
Density	0.923 g/cm^3
Melt index (190 ℃ / 2.16kg)	2 g/10 min
Peak melting temperature	110℃

Fumed silicon dioxide is produced by the vapor-phase hydrolysis of silicon tetrachloride in an H_2/O_2 flame. Rigid inorganic nanoparticles, for instance, calcium carbonate, silica, etc, cannot only toughen XLPE materials but also improve their tensile strength, electric properties, heat resistance and radiation resistance [18], [19]. In this paper nono-silica is AEROSIL 300. Table (2) shows the properties of the SiO_2 nanofiller.

Table 2: Properties of Silica-Nanofiller Material

Properties	unit	value
Specific surface area (BET)	m^2/g	270-330
pH value in 4% dispersion		3.7-4.5
Loss on drying	%	1.5
Tamped density	g/l	Approx.50
Sio_2content based on ignited material	%	99.8

2.2. Samples preparation

The pilot extruder blended the XLPE polymer material with silica nanocomposite. Extruder supplier has screw diameter 45mm and compounding temperature 120 ℃ to integrate the components homogenously. The novel nanocomposite cable insulation material had been cooled by cold water then dried by hot air at temperature 55-65 ℃ . The obtained compound XLPE/SiO_2granuleshad molded in hot press machine with temperature at a 180 ℃ for Period of 15 minutes then cooling till ^{60}Co Sheet thicknesses 1- 2 mm, with dimension 20x20 cm and Pressure 300 Pa. These molded sheets are cut into two types:

- Dumbbell shape samples according to ISO 527 for testing the tensile strength and elongation
- Cubic shape with dimension 10x10 cm testing the electrical properties.

3. System measurements

The system measurements will be accomplished as follows

3.1. Scanning electron microscope (SEM)

The samples microstructure surfaces were examined using the Scanning Electron Microscope (SEM) of type Jeol-T 20 – 200,000 (Japanese Brand) at various magnifications at different zones of composite material.

3.2. Mechanical measurements

Tensile strength and elongation tests were performed according to standard BS EN 60811. These were done in El-Sewedy Electric – Egyplast laboratory measurements in Egypt. Dumbbell shape samples according to ISO 527 samples were cut parallel and perpendicular to the extrusion direction is shown in Fig. 1. All the tests were performed at room temperature.

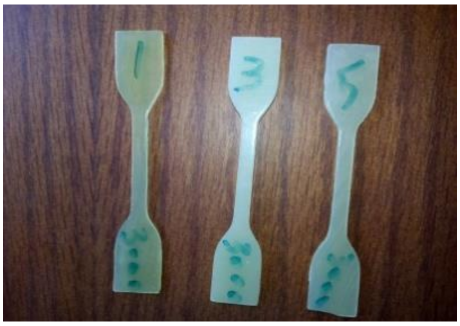

Fig. 1: Dumbbell Shape Samples According to ISO 527.

3.3. Electrical measurements

The breakdown voltage and the leakage current were carried according to An American National Standard (D 149-97a) as in figure (2-a) [20]. These measurements were done in the National Institute for Standards under supervision by the Ministry of Scientific Research in Egypt. The Alternating voltage at power frequency (50 Hz) is applied to a test specimen and the voltage is increased from zero, in Method A (Short-Time Test), until dielectric failure of the test specimen occurs. The test voltage is applied using simple test electrodes on opposite faces of specimens as in figurer (2-b). The suitable rate-of-rise is 1500 V/s and an average time of breakdown is 18 s. The leakage current is recorded according to customer requirements. The Test is repeated 2times.

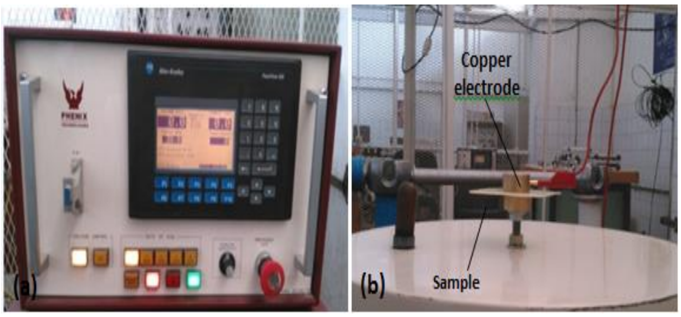

Fig. 2: (A) Alternating Voltage Supply with Test Cell, (B) Electrodes of Test Cell Rounded by Insulating Materials to Eliminate the Stray Capacitance.

The capacitance and dielectric properties of the materials were measured at room temperature (25 ± 1°C) by tester ASTM D-150; electrodes were deposited onto both surfaces of the specimens by sputtering. The diameter of the sputtered electrodes is 7cm.

3.4. Gamma-ray radiation measurements

The gamma radiation source used for Irradiation of Samples was ^{60}Co source of gamma facility Canadian Gamma cell (Ge-220) and represented at National Center for Radiation Research and Technology (NCRRT), Egyptian Atomic Energy Authority (EAEA), Cairo, Egypt. The device was produced with the specification given in table (3).

Table 3: Specification of Gamma Radiator

Specifications	^{60}Co
Irradiator Activity	2651 curie
Dose rate	1.87 KGy/h
Temperature of Chamber	50 ℃

4. Results and discussion

4.1. SEM of XLPE/SiO2 nanocomposites

The samples microstructure surfaces were examined using the Scanning Electron Microscope, figure 3 (a, b, c and d) illustrate the SEM micrographs of XLPE polymer material with silica nanocomposite blends as well as 1wt% of nano- SiO_2 with exposure to different irradiation doses, 50,100,300and 500 KGy as respectively. The trend of the mechanical properties is well explained by observing the SEM micrographs. In figure 3.b it is seen that there is proper dispersion of the matrix and this is a reason for the maximum enhancement of mechanical properties at 1 wt% nano- SiO_2 containing composites. It may be observed that the structure improvement and mechanical properties for all samples 1wt% nano- SiO_2 increase with increasing the irradiation dose up to 100 kGy. This increase is affiliated with the formation of a higher number of crosslinks leading to better interaction between the nanoparticle and the polymer matrix. At higher doses beyond 100 KGy, the properties start to decrease with increasing irradiation dose up to 300KGy (figure 3.c) and 500KGy (figure 3.d), this decrease in properties due to degradation process in a matrix of material [21].

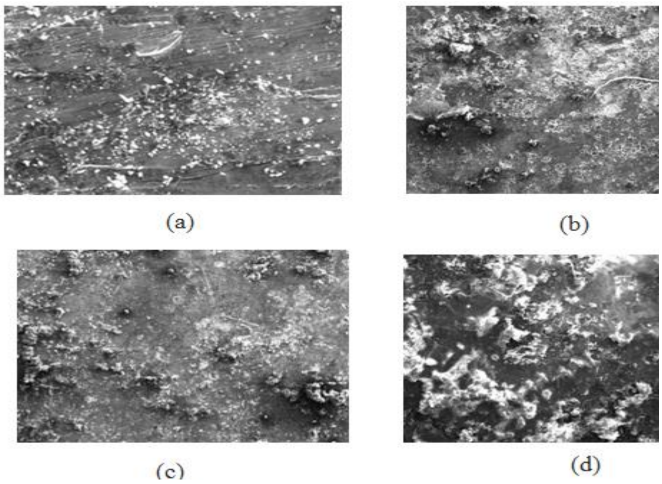

Fig. 3: The XLPE with 1% of Nano-Sio_2 Contents as A Function of Irradiation Doses, A. 50kgy, B.100 KGY, C.300 KGY, and D.500 KGY

4.2. Mechanical properties of the cable

Figure 4 illustrates the different reactions occurring at the interfaces have failed to explain the exact role of nanoparticles in enhancing the properties of silica nanocomposites compound with XLPE cable insulation under the effect of gamma radiation. The common assumption in all proposed results is that structural properties in the interface layer are changed, which results in structural and chain dynamic changes around the silica nanoparticles. This may stand as justification for a change in the surface structure of nanocomposite. As received value of tensile strength for (1%, 2.5%, 4%, 5%) $XLPE/SiO_2$ are (17.18), (19.4), (19.16), (13.33) N/mm^2 respectively, without exposed to radiation. While exposing the samples to different radiation dose, as in (Figure 4), which observe tensile strength gradually decay with increase the radiation dose until 200 kGy then the particle rearrange together and cross-linked that causes filling to the surface area, observe tensile strength began to increase again. Once mixing the cable with 4% of the nano-silica it gives the best performance of resistance to radiation and as noted that the dose of 50KGy to 300 KGy gradually decreasing tensile strength with stability for a period and the interruption is gradual rather than rapid.

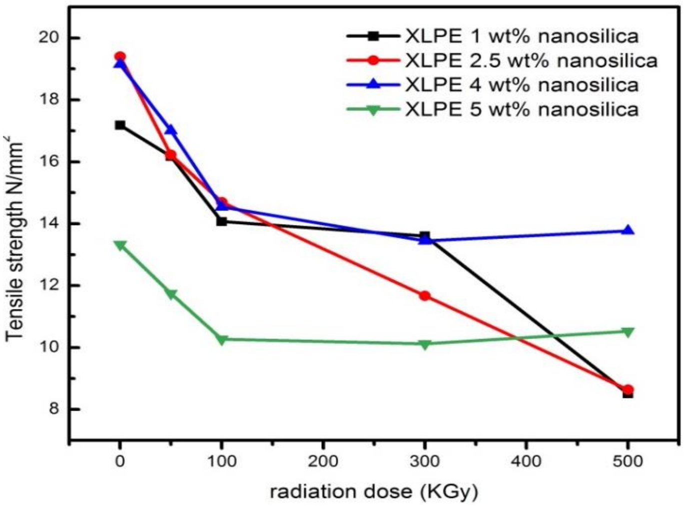

Fig. 4: Tensile Strength of Different XLPE/Sio_2 Nanofiller at Different Radiation Doses.

One can see the nanofiller injection ratios have better behavior for the all cable corresponding to radiation dose at 50kGy as shown in figure (5), where the elongation is 722.89, 460.33, 455.02 and 352.51% for $XLPE/SiO_2$ (1%, 2.5%, 4%, 5%) respectively. In the case of an increase in radiation doses after 50kGy, there an exponential decrease in the value of elongation. Not that in increasing radiation to 200 and 500, there is a disturbance in the order of atoms on the insulation surface of all cables mixed with Nano silica except $XLPE/SiO_2$ cable with 1% concentration; it is more stable with increased radiation dose and gives the best performance of elongation. Thus, the mechanical properties of cable insulators improve at low doses of radiation and when mixed with small percentages of nanoparticles.

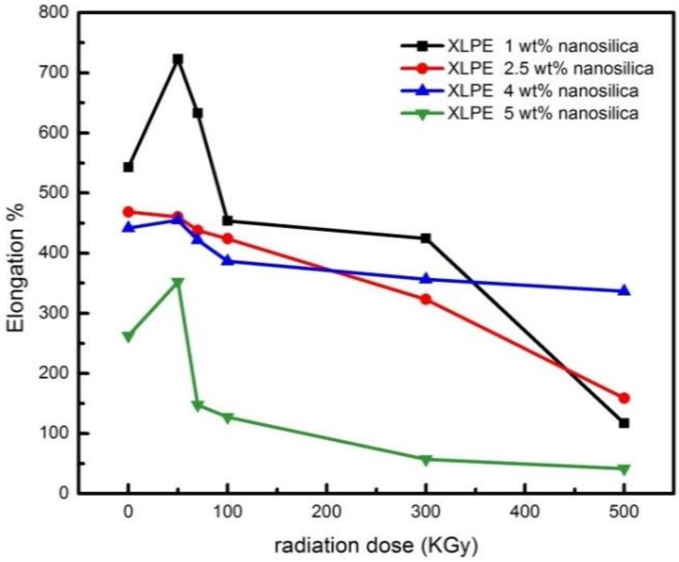

Fig. 5: The Elongation of Different XLPE/Sio_2 Nanofiller at Different Radiation Doses.

4.3. Electrical properties

The AC breakdown voltages of all tested cable samples with nanosilica shown in figure (6) shows variable values with increase the radiation dose. For increase, the area under curve represents the enhancement in breakdown voltage so gives beast electric property for cable insulation; in above figure show the 1% and 4% $XLPE/SiO_2$ curves gives the better breakdown voltage in range of radiation doses. This shows that when cables are exposed to low doses of radiation, they increase the interfacial interaction region as well as improved this electric property. At 100 kGy the value of the breakdown voltages is 30KV and 29.5KV for 1% and 4% $XLPE/SiO_2$ respectively. Specifically one can recommend the nanofiller improve the electric characteristic of the power cable for specific limited operation condition. A lot of testes and results are, therefore, required for the neat description of the under test cables.

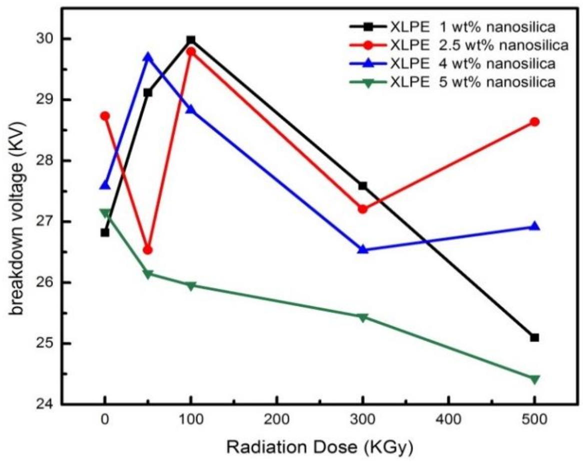

Fig. 6: The Breakdown Strength of Different XLPE/Sio$_2$ Nanofiller at Different Radiation Doses.

Fig. 7 show the leakage current for different XLPE/SiO$_2$ concentration cables that exposed to different radiation doses, that it starts at zero radiation dose, the value of leakage current is 0.6 mA for most types of different materials, and quickly increases to a final value of 1.2 mA for XLPE with 1% nano- clay at 50 kGy and 300 kGy, 1.4 mA for 2.5 % at 100 kGy, 1.4 mA for 4% at 50 kGy and 1.22 mA for 5% at 500 kGy. This is the way that good insulation behaves. The other change may be that, instead of rising quickly to a final value and the leveling out, the leakage current simply may continue to increase and decrease with different radiation dosing rate.

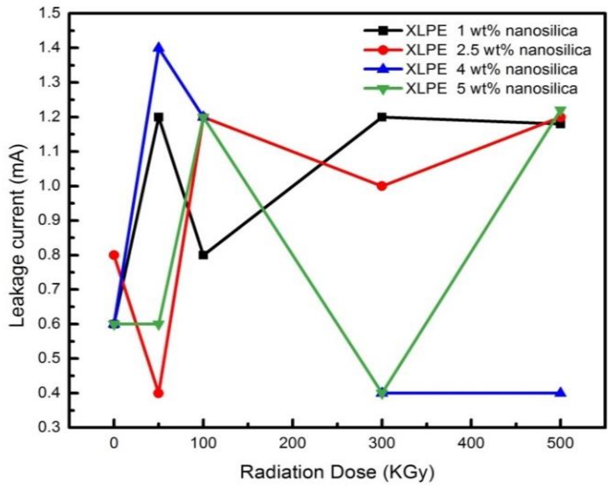

Fig. 7: The Leakage Current of Different XLPE/Sio$_2$ Nanofiller at Different Radiation Doses.

The concentrations of SiO$_2$ nanofillers of all the cable insulation except 5wt % causes decreasing in the capacity as shown in Figure8, an increase in the electric capacitance for XLPE/SiO$_2$ cable insulator with nano concentration of 5% to 95pF at 50 kGy. On the other hand, fillers of 1%, 2.5%, and 4% cause gradually decay of cable insulation capacitance. During radiation doses from 100 kGy to 500 kGy, find that all cable with different mixing rates have stability. XLPE assorted with the nano-silica has a distinguish changes of the insulation capacitance at each filing time with the radiation doses, zero dose yields (92pF) for XLPE/SiO$_2$ with 1%nano filler, while for example, 5% produces 70pF.

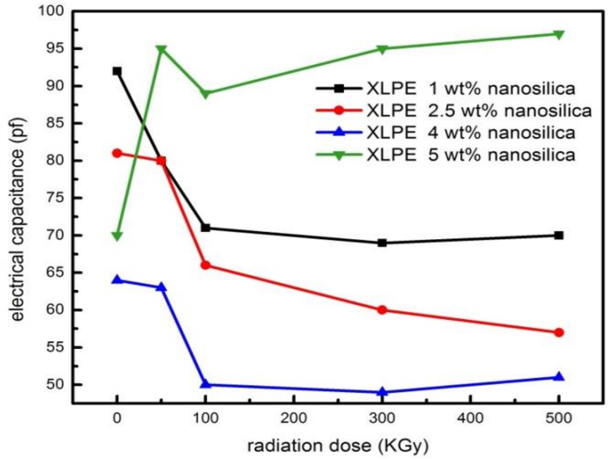

Fig. 8: The Capacitance of Different XLPE/Sio$_2$ Nanofiller at Different Radiation Doses.

During the low doses of radiation (50 to 500 KGy), high significant increasing of dielectric constant for XLPE/SiO$_2$ cable insulator with a concentration of 5wt % and the concentrations (1%, 2.5%, and 4%) causes gradually decay of dielectric constant as shown in Figure 9. The other doses of radiation after 50 to 500KGy), there were gradually decreasing of dielectric constant for XLPE/SiO$_2$ cable insulator concentrations (1%, 2.5%, and 4%) with complete stability for 5wt %.

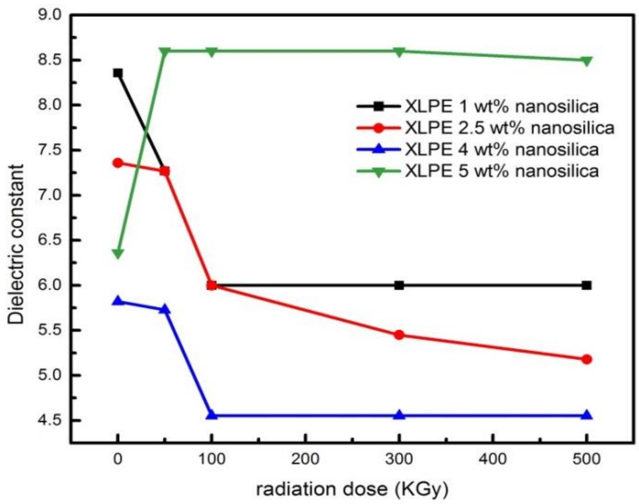

Fig. 9: The Dielectric Constant of Different XLPE/Sio$_2$ Nanofiller at Different Radiation Doses.

5. Comparison between pure XLPE cable and an ideal case of XLPE / Nanosilca

Figs. 10 and 11 tensile strength, which is an indication of the strength of the cable insulation material through a tensile test, but not sufficient alone, must be accompanied by a measurement of elongation properties to ensure that no cracks and brittleness are made to the cable insulation. The XLPE / SiO$_2$ cable at 1% concentration had the highest elongation without and when exposure to gamma radiation in the dose of 50, 100 and 300 KGy, the elongation value was 722.89, 453.67 and 424.34, respectively, compared to the XLPE cable at the same dose, while elongation, 443.08, 372.82 and 392 .04, respectively. In fact, nano silica has improved the insulation of XLPE cable to give the best mechanical properties.

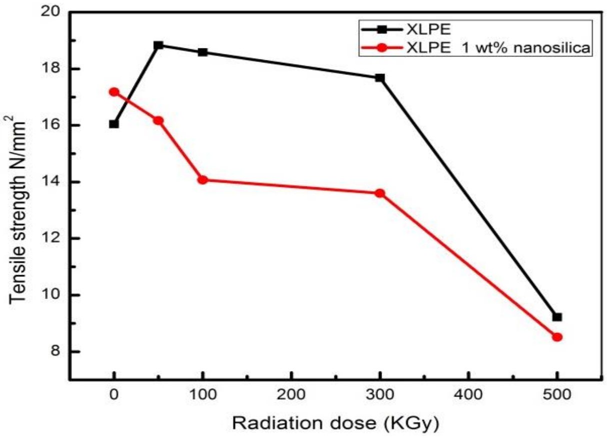

Fig. 10: Pure XLPE Cable and XLPE/Nanosilica with 1% Concentration for Tensile Strength Properties at Different Radiation Doses.

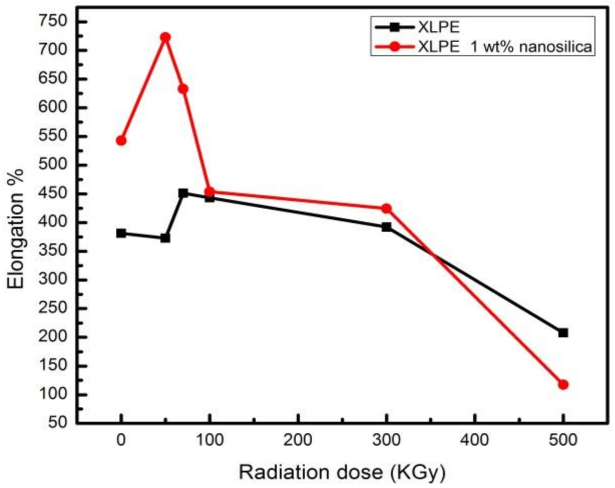

Fig. 11: Pure XLPE Cable and XLPE/Nanosilica with 1% Concentration for Elongation Properties at Different Radiation Doses.

Comparing the cable mixed by nano silica for 1% concentration with the unfilled cable as shown in Fig. 12, the highest value of AC breakdown voltages was 30 KV for XLPE/SiO_2 cable while 29 KV for XLPE cable. From this, we conclude that nano-silica has functioned to improve the electrical properties of the XLPE cable. The internal structure of the material becomes more intense and the porosity and interior voids decrease as a result of the removal of the mechanical stresses of the cable material when exposed to small doses of radiation, thus becoming more suitable for electrical properties and leading to improved electric capacitance and dielectric constant. Fig. 13 show pure XLPE and XLPE/SiO_2 have a high value of 1.2 mA for the leakage current at different radiation dose.

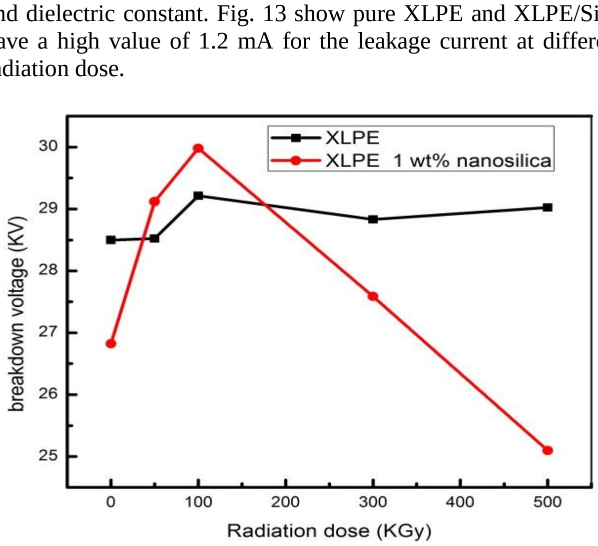

Fig. 12: Pure XLPE Cable and XLPE/Nanosilica with 1% Concentration for Breakdown Voltage Properties at Different Radiation Doses.

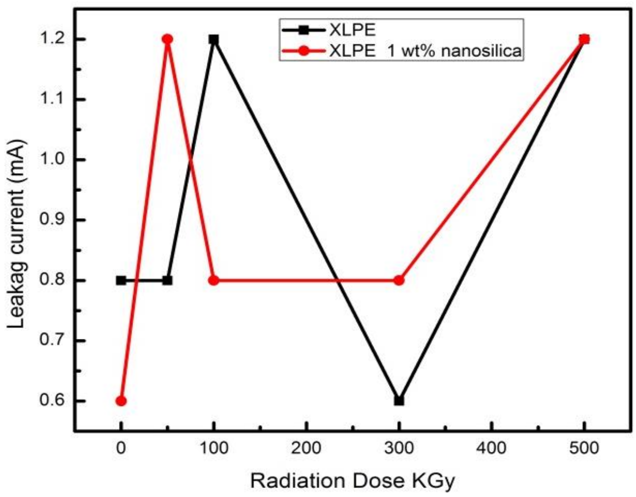

Fig. 13: Pure XLPE Cable and XLPE/Nanosilica with 1% Concentration for Leakage Current Properties at Different Radiation Doses.

The internal structure of the material becomes denser and the porosity and interior spaces decrease as a result of the removal of the mechanical stresses of the cable material when exposed to small doses of radiation, thus becoming more suitable for electrical properties and leading to improved electric capacitance and dielectric constant. Figs. 14 and 15 illustrate the increase in the values of these two characteristics of the cable XLPE mixed with nano-silica for the non-mixed XLPE cable.

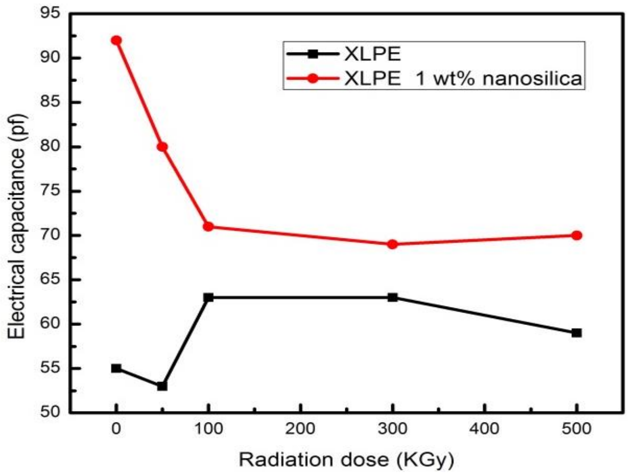

Fig. 14: Pure XLPE cable and XLPE/Nanosilica with 1% concentration for capacitance properties at different radiation doses.

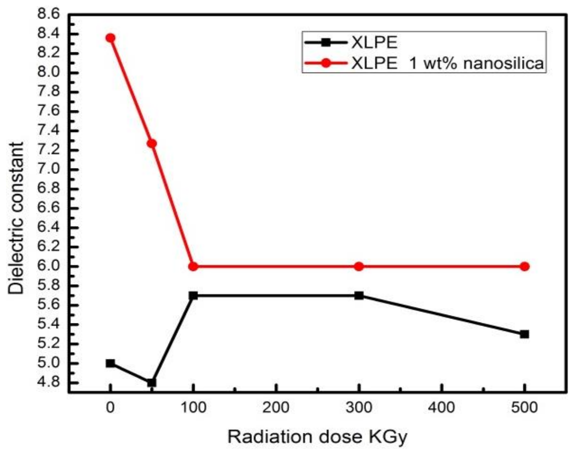

Fig. 15: Pure XLPE Cable and XLPE/Nanosilica with 1% Concentration for Dielectric Constant Properties at Different Radiation Doses.

6. Conclusions

The electrical and mechanical properties of XLPE/SiO_2 with deferent nano-filler concentration were investigated and compared with unfilled cable. It is found that XLPE/SiO_2 with 1 wt % have the highest ac breakdown voltages of 30KV at exposing to gamma radiation at 100 kGy resulting in a decreasing the conductivity and then improvement the electrical characteristics. Although the tensile strength for 1% XLPE / SiO_2 decrease with increasing the radiation dose, the elongation has been increased and consequently more elasticity and stability in the mechanical properties will be established.

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